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Major Goals: US Army personnel are heavily engaged in distant counter insurgency (COIN) operations that challenge conventional warfighting doctrine and technologies. Improvised Explosive Devices (IEDs) have become the “weapon of choice” of insurgents attacking American soldiers and nearly two thirds of combat-related deaths in Iraq have been caused by this type of munition. The Department of Defense (DoD) has funded research aimed at developing ultra wideband (UWB) radar and staring optical sensors to provide improved detection capability. Experimentation has demonstrated that despite high potential, new signal processing approaches will be necessary to minimize excessive numbers of false alarms. Delaware State University (DSU) along with our partners at University of Delaware (UDel) and Pennsylvania State University (PSU) believe we have the ability to deliver outstanding and relevant algorithms to enable new systems under development to reach the high performance our Warfighters demand and deserve. Thus we are pleased to offer the Center for Advanced Algorithms (CAA) whose primary goal is to exploit applied mathematics, computer science and electrical engineering to develop key enabling algorithms to support and improve remote sensor systems currently under consideration or already deployed to defeat IEDs.

Accomplishments: Delaware State University (DSU) staff along with partners from the University of Delaware (UDel) and Pennsylvania State University (PSU) have undertaken a focused effort to develop and mature technologies to detect and locate Improvised Explosive Devices (IED) under the direction and sponsorship of the US Army Research Laboratory (ARL). The program solicitation emphasized the importance of transition of technology into ARL programs. Army sponsors coined the name Partnership for Innovative Research Transition or PIRT to highlight this goal. Responding to this direction, we combined specialists in Electromagnetic Modeling, Signal and Image Processing, Radar Transceiver Design, and Multi-Sensor Fusion in a concentrated effort to improve the ability of ground-based sensor platforms to reliably “see” and locate both surface and underground IEDs. At the prompting of the Army, we emphasized transition of applicable technology into the ARL trial programs where novel technology is exercised in realistic field conditions. As such, we developed advanced synthetic aperture radar (SAR) processing techniques in order to reduce multiplicative image noise and assisted ARL personnel in porting the necessary algorithms into their mainline image processing facility. We designed and implemented an advanced radar transceiver with unprecedented spectral control and delivered it to ARL for use in their multi-sensor testbed. We built software codes to enable the geo-referencing of image products from disparate sensors such as forward-looking ground penetrating radar (GPR), forward-looking infrared cameras (FLIR) and standard television cameras. These codes were delivered to ARL for inclusion in their sensor testbed and our team assisted in various data collection exercises side by side with Army personnel. Finally, we are most proud that members of our research team spent countless months working at the ARL facility in Adelphi with the Army team to ensure that our research would be of maximum value. This resulted in more than one of the team members being hired by the Army to carry this work forward.

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14. ABSTRACT
In this report, we describe the goals and accomplishments of the effort led by Delaware State University with significant assistance from Penn State University and the University of Delaware to develop advanced technology to defeat Improvised Explosive Devices. Under the direction of the US Army Research Lab (ARL), our team complemented Army efforts to improve the image quality of a forward looking ultra wideband (UWB) radar compatible with a ground vehicle, designed an improved radar transceiver to provide a more controllable transmitted spectrum and developed software to geo-reference data streams from disparate sensors and present a composite picture to the operator. A major goal of the Army program was to ensure timely and effective transition of technology into programs of interest to ARL and our team emphasized this need by working side by side with Army counterparts throughout the time of the undertaking. Products of this effort include: improved image processing algorithms, novel RF transceiver architectures and software for geo-referencing and visualization.

15. SUBJECT TERMS
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INTRODUCTION

Delaware State University (DSU) staff along with partners from the University of Delaware (UDel) and Pennsylvania State University (PSU) have undertaken a focused effort to develop and mature technologies to detect and locate Improvised Explosive Devices (IED) under the direction and sponsorship of the US Army Research Laboratory (ARL). The program solicitation emphasized the importance of transition of technology into ARL programs. Army sponsors coined the name Partnership for Innovative Research Transition or PIRT to highlight this goal. Responding to this direction, we combined specialists in Electromagnetic Modeling, Signal and Image Processing, Radar Transceiver Design, and Multi-Sensor Fusion in a concentrated effort to improve the ability of ground-based sensor platforms to reliably "see" and locate both surface and underground IEDs. At the prompting of the Army, we emphasized transition of applicable technology into the ARL trial programs where novel technology is exercised in realistic field conditions. As such, we developed advanced synthetic aperture radar (SAR) processing techniques in order to reduce multiplicative image noise and assisted ARL personnel in porting the necessary algorithms into their mainline image processing facility. We designed and implemented an advanced radar transceiver with unprecedented spectral control and delivered it to ARL for use in their multi-sensor testbed. We built software codes to enable the geo-referencing of image products from disparate sensors such as forward-looking ground penetrating radar (GPR), forward-looking infrared cameras (FLIR) and standard television cameras. These codes were delivered to ARL for inclusion in their sensor testbed and our team assisted in various data collection exercises side by side with Army personnel. Finally, we are most proud that members of our research team spent countless months working at the ARL facility in Adelphi with the Army team to ensure that our research would be of maximum value. This resulted in more than one of the team members being hired by the Army to carry this work forward.

BACKGROUND

Background: The US warfighter faces distant insurgencies that challenge conventional military doctrine and currently available technology solutions. Insurgents have developed low tech but highly effective tactics to deny basic security to local populations through the use of car bombs, suicide vests and improvised explosive devices (IEDs). Many of these same weapons and tactics are used against our service personnel leading to high casualty rates and diminishing support for these operations at home.

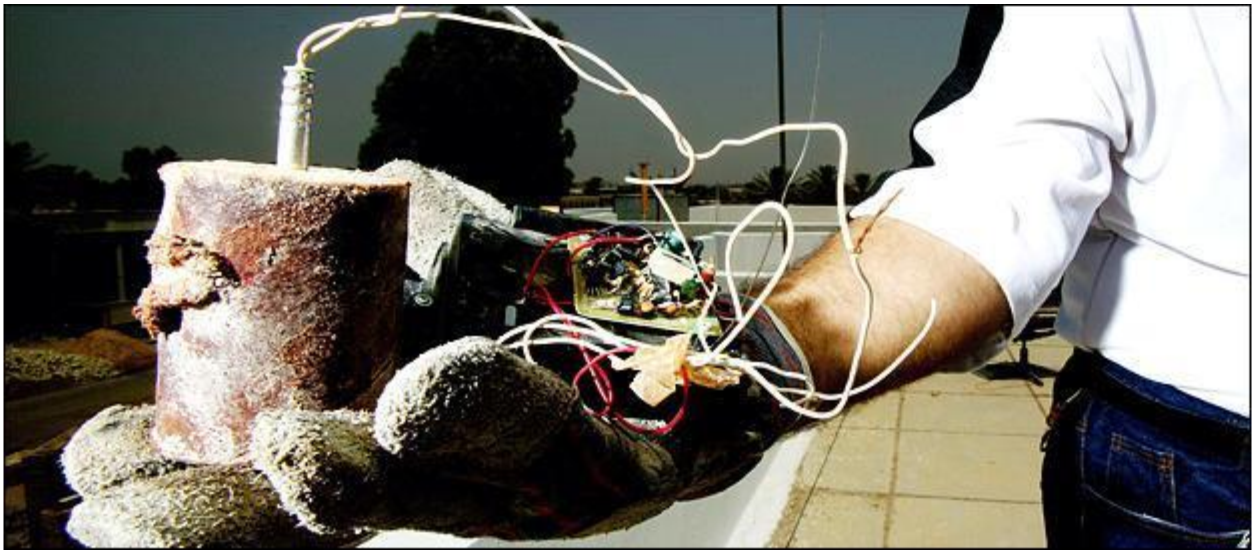
Aftermath of IED Attack

Urban Operations

Insurgents have become skilled at the use of conventional munitions (such as artillery shells and mines) and existing technology (such as cellphones for triggering devices) to produce highly effective IEDs. Such devices have accounted for the majority of US military deaths in Iraq.

Also, combat operations conducted in urban areas have resulted in high numbers of casualties and, at times, significant collateral damage. For instance, a US Marine Corps operation in Haditha, Iraq led to many civilian casualties and serious controversy at home. Thus, a major issue for the warfighter is isolating enemy combatants in highly populated civilian centers.

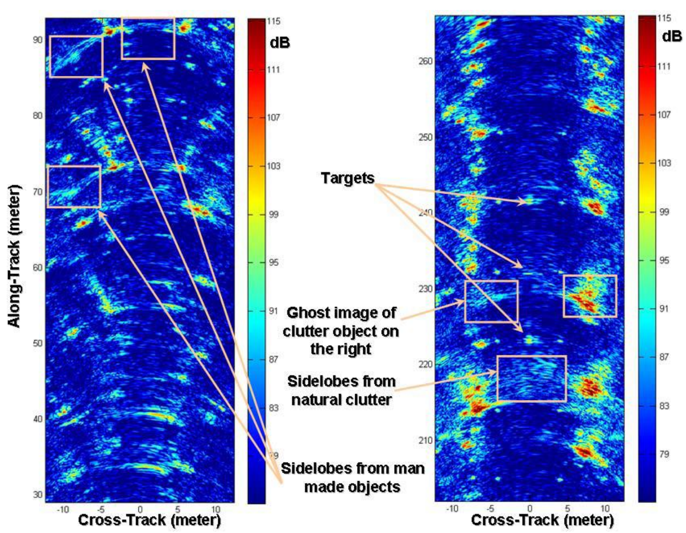
The common denominator of current insurgent tactics is the use of camouflage, concealment and deception (CCD). These tactics include IEDs buried under a road surface, car bombs and enemy combatants mixing with civilian populations and seeking concealment within a typical urban structure.



Unfortunately, conventional sensor technology offers only limited solutions for these scenarios. Thus, the PIRT team embarked on a concerted effort to aid Army engineers in developing new capabilities to defeat IEDs.

Program Undertaken: At its inception, the PIRT team's effort consisted of several major thrusts:

1. **Reduction of Image Noise in Forward Looking Radar Imagery.** Prior exercises and trials undertaken by Army researchers that utilized forward-looking radar had disappointed senior Army leadership. Though targets of interest were often noted in radar imagery, competing clutter often overwhelmed automatic detectors that were trained to isolate targets from clutter. This is clearly seen in the image (courtesy of ARL) shown below:



Discovering and implementing techniques to "clean up" such multiplicative noise would be essential to improving radar performance.

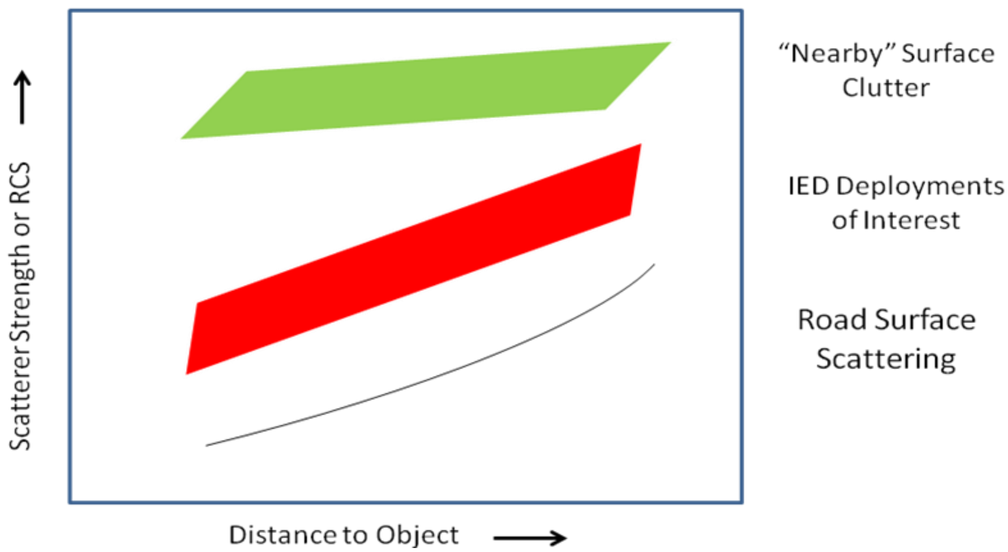
2. **Development of advanced radar transceiver hardware to provide flexibility** in radar spectral coverage. ARL has been a pioneer in the development of impulse technology to provide ultra wideband (UWB) radar capability for penetration through obscuring materials such as tree canopy, walls and the ground. However, this technology afforded limited control of the exact radar spectral coverage. Operating in the same bands as broadcast communications, GPS and other essential services, this could prove to be a significant limiting factor in the use of such a radar. The PIRT team worked collaboratively with the Army to design and develop a novel radar transceiver that provided significant control over spectral coverage. This transceiver was designed as a "drop-in" component to the balance of the ARL radar.
3. Study to determine the **value of inverse scattering methods** to improve image formation quality of forward-looking radar. One of the most exciting topics in leading edge research is the development of algorithms to invert electromagnetic scattering behavior to isolate the shape of an object under radar illumination. The team had a two part approach to this topic – one, improve and utilize electromagnetic solvers to understand and characterize the scattering phenomenology of targets of interest and, two, develop algorithms to exploit the inverse problem to generate improved images. Unfortunately, we lost our lead investigator on the second part of the planned effort and only made significant progress on the first.
4. At program inception, ARL personnel had a pressing need to combine outputs from separate optical and radar sensors. They requested that our lead optical investigator deviate from a planned effort on optical change detection and, instead, look at an **improved multi-sensor fusion paradigm** from a forward-looking, ground-based testbed that combined day TV, radar and FLIR. This required first geo-referencing the three sensor outputs and then combining them in an "augmented reality" presentation for the operator. The ultimate goal for the Army is to use the common referenced data sets to improve the detection rates of IED targets.

Accomplishments

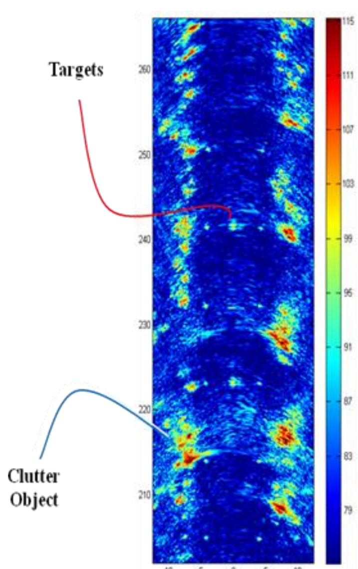
Reduction of Image Noise in Forward Looking Radar Imagery. Forward-looking, ground-penetrating radar offers critical benefits to the IED detection mission: the ability to penetrate both the ground as well as materials often used to conceal the presence of an explosive device and standoff detection to protect the measurement asset and operating personnel. Below we show a simplified on-route IED detection mission. An IED (in this case a 155mm artillery round) is place along the side of the road with a triggering device set to detonate as the convoy speeds by. Note most missions will be significantly more difficult than this simple example:

Researchers at ARL and the Army's Night Vision and Electronic Systems Directorate (NVESD) have developed advanced experimental platforms and conducted measurement campaigns to characterize and explain target and clutter scattering phenomenology with various road surfaces and target emplacements. Below we show the ARL testbed. Mounted atop the vehicle is a forward looking wideband radar:

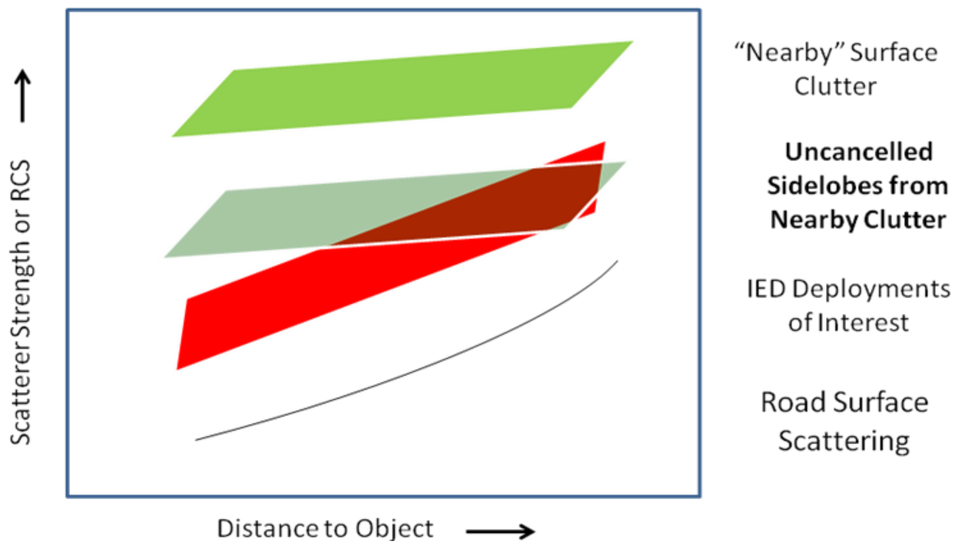
These measurement efforts coupled with extensive EM modeling activities have resulted in an important knowledge base of the Radar Cross Section (RCS) of many targets of interest versus background clutter (as well as system noise characteristics of the measurement instruments). Below, using notional values, we show the relative strength of the targets of interest versus the road surface scattering in direct competition. Notice the targets are much stronger. However, nearby surface clutter such as bushes and trees can be quite strong. Normally, we would hope that their positional offset from the road surface would allow us to separate this clutter from the roadway IEDs.



In this scenario, we should be able to reliably separate targets from clutter. However, sidelobe generated artifacts alter this basic conclusion. Below we show measured data from the ARL testbed using conventional image formation based on backprojection techniques:

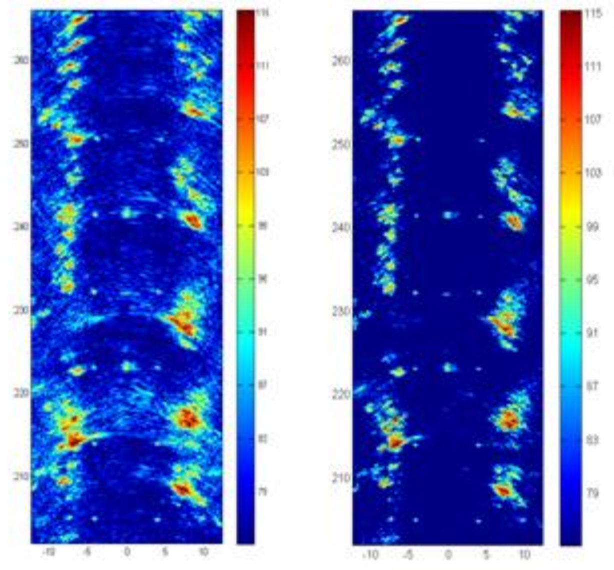


In this false-color encoded image of radar cross section versus position, note how strong patches of clutter “smear” sidelobe energy across the road surface (down the centerline of the image). Targets in those areas are overwhelmed by the sidelobe cross section. Thus the ARL measurement program has provided convincing evidence of the crucial role sidelobe-based or multiplicative noise plays in achieving reasonable detection performance. Artifacting or sidelobe migration competes powerfully with weak targets leading to potentially disastrous numbers of clutter-induced false alarms. We modify our preceding notional chart to correctly account for the role of uncancelled sidelobes. Note how the radar cross sections now compete nearly directly in effective RCS.

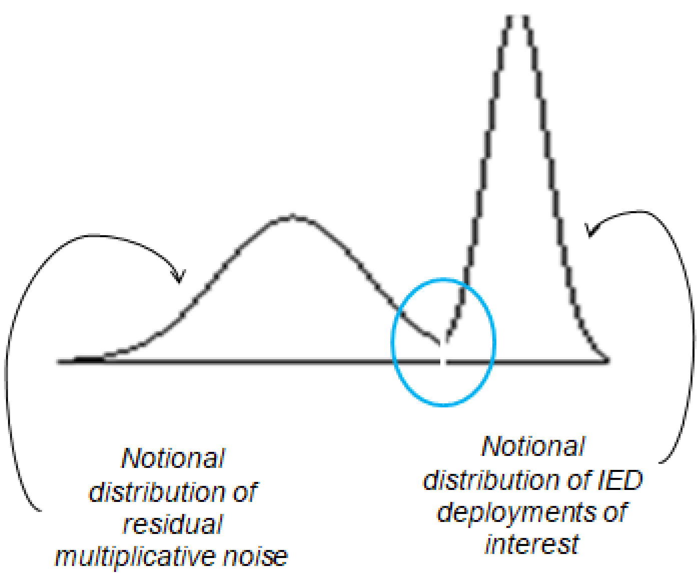


This is especially true in a crucial scenario for US Service personnel – on-route IED discovery where clutter-related sidelobes smear across the road surface leading to intense competition with the weak RCS associated with buried or partially-buried IEDs. As a result, the false alarm performance realized to date in experimental programs has not satisfied military leadership.

Recognizing the root cause of disappointing detection performance for radar-based approaches, the DSU team worked collaboratively with ARL researchers to develop new non-linear based processing schemes to tame unwanted sidelobe behavior. We recognize that although the forward-looking imaging geometry provided a rich and full aperture of data collection points, the fundamentally limited synthetic aperture still affords many opportunities for erratic sidelobe performance. By randomly sub-sampling that same collection of aperture points repetitively, forming images and then recursively minimizing the result, however, only scattering from actual objects would (in the limit) remain. The so-called recursive minimization algorithm, when applied to real world data, was stunningly effective as we see in the side by side result below. On the left, is a conventionally formed image with noticeable artifacting. On the right, is the recursively formed image with the poor sidelobe behavior improved. ARL has now adopted this method into its mainline signal processing regimen.



Because of the much reduced image noise, separation of targets from clutter along the roadway is significantly enhanced. Notionally, we show this below:

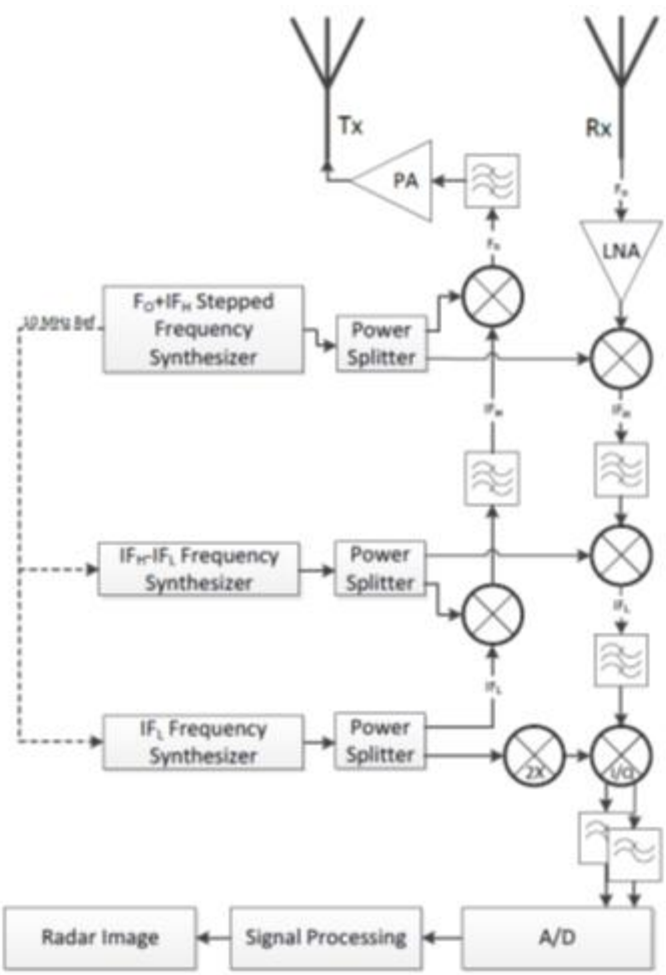


The PIRT team, working in close collaboration with Army researchers, has developed novel non-linear approaches to image formation which offer a significant reduction in clutter-based noise competition. For on-route IED discovery, improvement in detection performance is clear.

Development of advanced radar transceiver hardware to provide spectral flexibility. As part of the PIRT effort, we completed the design, implementation, and verification of an ultrawideband (UWB) stepped-frequency ground-penetrating radar (GPR) transceiver. The main goal of the Spectrally Agile

Frequency-Incrementing REconfigurable (SAFIRE) system has been to preserve the ability to detect buried and concealed landmines and IEDs from safe stand-off distances that the prior ARL Impulse Radar demonstrated while maintaining this performance in the presence of radio frequency interference (RFI). Unlike impulse-based UWB radars, stepped frequency radars (SFR) have the capacity to excise specific frequencies within their operating band, thus reducing interference to nearby systems. Furthermore, through spectral sensing techniques, the frequency bands where RFI is present can easily be removed. Because of the inherent flexibility of being able to program and select basic stepped-frequency radar frequencies, the SAFIRE system can avoid those spectral areas with high RF content while still achieving ultra wideband operation for precision range resolution and penetration. Verification of the system's operational specifications was completed via laboratory measurements and theoretical analysis; the laboratory measurements included transmitted power, spectral purity, receiver gain, receiver noise figure, receiver noise floor, dynamic range, antenna measurements, and overall susceptibility to RFI. Thinned spectrum algorithms have been developed and provided to the Army as part of this undertaking.

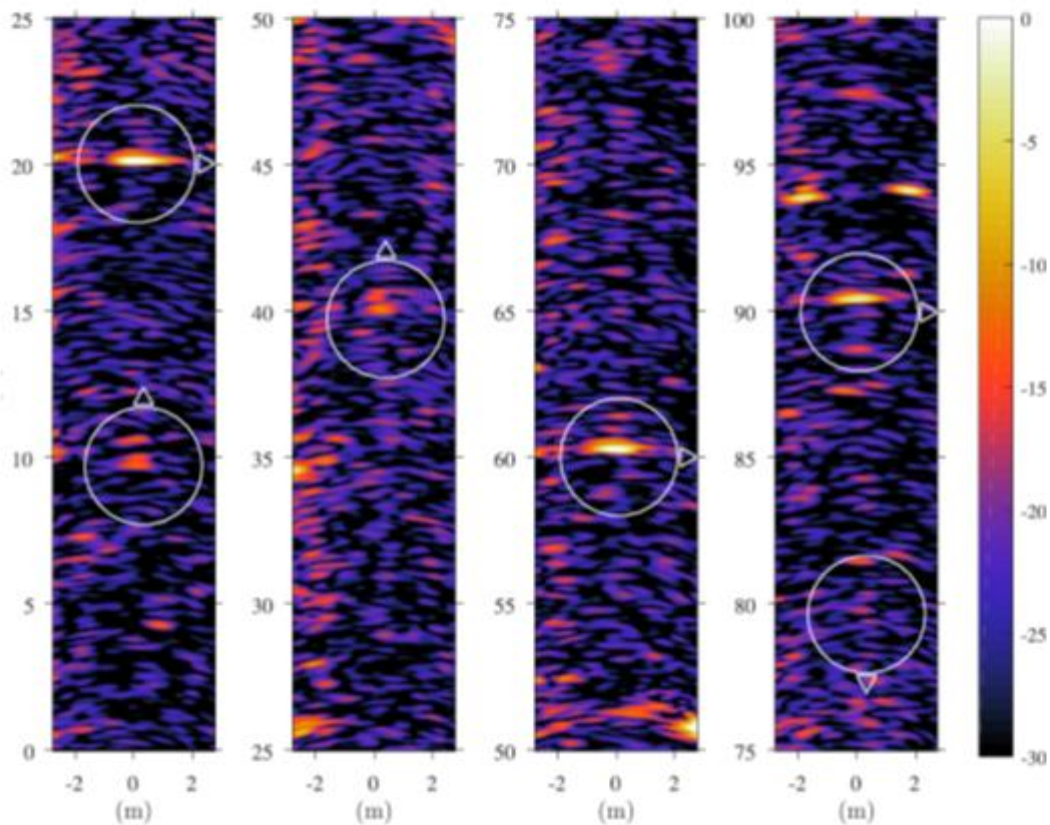
A block diagram of the SAFIRE system is shown below:



It is a completely capable, ultra wideband architecture consistent with the Army goal to incorporate a forward-looking radar on a ground vehicle.   Shown below is initial hardware being tested near the Penn State University campus.

The hardware has been designed and built with the participation of Army researchers for inclusion in the Army forward-looking testbed.

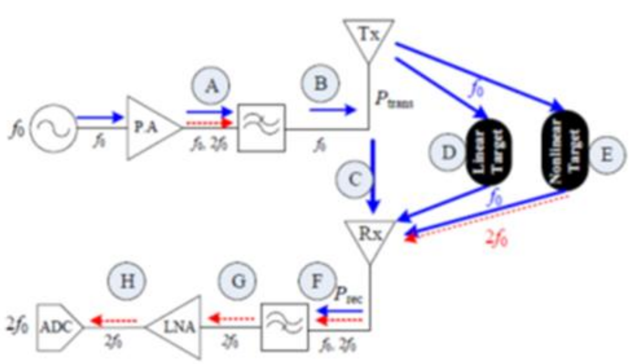
During the design process, initial hardware was trialed at an arid US Army test site jointly with Army personnel and the test images associated with the collection program are shown below:



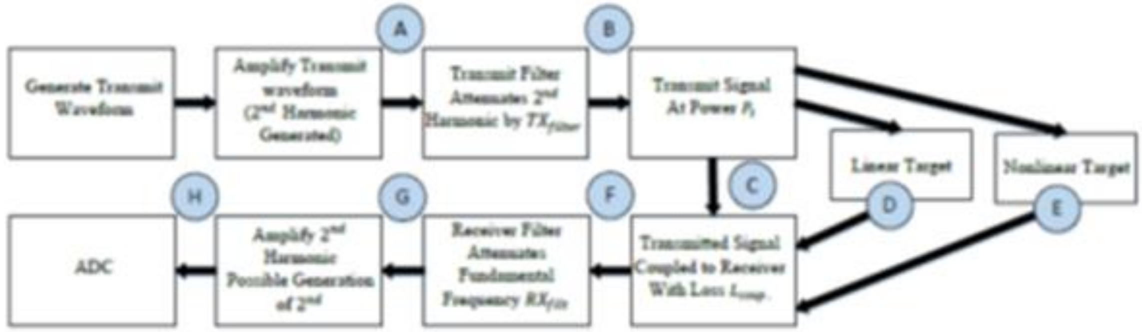
These results are similar to the impulse radar that the Army has used on many prior collections and signal that the hardware maturity is sufficient to adopt the hardware into the mainline Army experimental test efforts.

A second phase of this effort was to examine the effectiveness of using supplemental hardware to examine the potential for “harmonic” radar in the IED defeat mission. The existence of nonlinearities in electrical circuits is well known. Circuit components such as diodes, amplifiers, and mixers are known to exhibit nonlinear behavior. In the case of diodes and mixers, their nonlinear properties can be exploited to perform meaningful tasks. The nonlinear properties of diodes are used to rectify signals and mixers are used to up-convert and down-convert signals from one frequency to another. Rectification and up-conversion are nonlinear operations. Since the 1970s, nonlinear effects in circuits have been exploited for remotely detecting the presence of electronic circuits. This is done by actively probing a circuit, at a standoff distance, and processing the received nonlinear signals produced by the circuit. A specialized radar tailored to a set of RF electronic responses would allow security personnel to detect unauthorized radio electronics in restricted areas, or enable first-responders to pinpoint personal electronics during emergencies. The advantage of using nonlinear detection over traditional detection techniques is that most naturally occurring objects, like trees, bushes, rocks etc., do not exhibit this behavior. Therefore, a nonlinear radar system will ignore any natural linear clutter and detect only targets possessing nonlinear properties. The challenge of this type of radar is that it requires a high power density impinging on the target, and a highly linear, high dynamic range receiver to capture the weak nonlinear returned signal. Many groups have studied the problem of detecting nonlinear junctions at a distance. These systems traditional use a single frequency waveform and a single transmit and receive antenna. With this type of configuration only detecting nonlinear targets is possible. No ranging, tracking, imaging or identifying nonlinear targets can be done. Using a single frequency also make the system hardware much simpler, as it is much easier to build filters, amplifiers etc. at a single frequency or within a narrow band of frequencies. Designing and developing a nonlinear radar system with a wide bandwidth is far more difficult. Without utilizing bandwidth for resolution and an aperture for cross range resolution, locating the position to nonlinear targets would not be possible.

Recognizing the challenges, the PIRT team set out to build a nonlinear or harmonic UWB radar transceiver under ARL direction. The lynchpin of the radar system is a highly linear transmitter coupled with a highly linear, high dynamic range receiver:



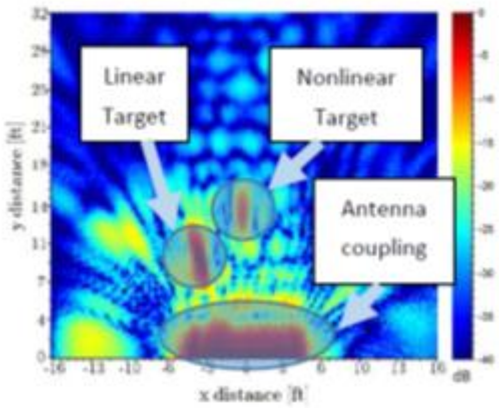
In the figure below, we show the block diagram of the novel harmonic system:

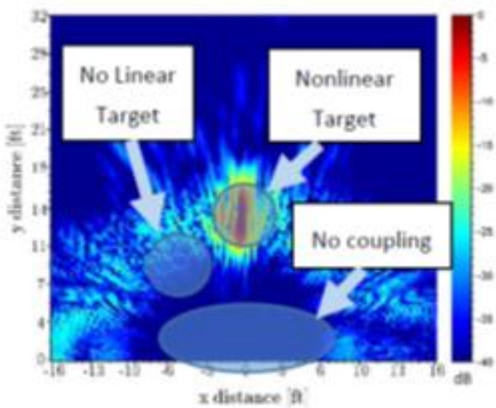


If the target has a non-linear reradiating element (such as a mixer diode), a second harmonic product is also present in the backscattered signature though generally quite weak in comparison to the direct backscatter. With a properly designed second harmonic receiver, such a signal can, in principle, be detected in the composite signal. The key thing is ONLY man made targets (and, generally, only those with significant electronic content) will evidence a second harmonic signal – thus, this approach can provide direct sub-clutter visibility for these targets. The PIRT team worked closely with Army engineers to design and build such a system to enable ARL personnel to investigate the efficacy of this technique under realistic test conditions.

As part of this program, linear and nonlinear SAR data were collected on both targets present in the scene using both the linear and the nonlinear radar. The nonlinear mixer target was placed at *x-y* coordinates (0, 15 ft) and the linear corner reflector as placed at *x-y* coordinates (−3 ft, 12 ft). Synthetic aperture radar (SAR) images of linear and nonlinear targets using both linear and nonlinear radar data were formed. The SAR images demonstrate the clutter suppression capabilities of nonlinear radars. Receive power vs. frequency data are used as features to classify five different nonlinear targets. Classification results for five different electronic targets have been tabulated and provided to the Army. Additionally, data were taken of a slow-moving nonlinear target and range Doppler plots were reviewed with ARL. Data were measured showing detection of a nonlinear target 25 feet from the radar with more than 20 dB signal to noise ratio. These data were used to estimate the maximum detection range of the system to be at least 50 ft – consistent with an Army standoff detection mission.

The linear and harmonic SAR images are presented below. The linear response shows the corner reflector and mixer at the correct locations, while the nonlinear radar only shows the mixer (with its non-linear re-radiating element) and suppresses the corner reflector. Although the corner reflector was present in the scene while the nonlinear data were collected, it does not appear in the nonlinear SAR image in the lower panel of the figure below. This clearly demonstrates the advantage of nonlinear radar in detecting only nonlinear targets. The antenna coupling also shows a strong response in the linear SAR image, and it stays in the same range bin regardless of aperture position; thus, it is observed along the entire aperture.



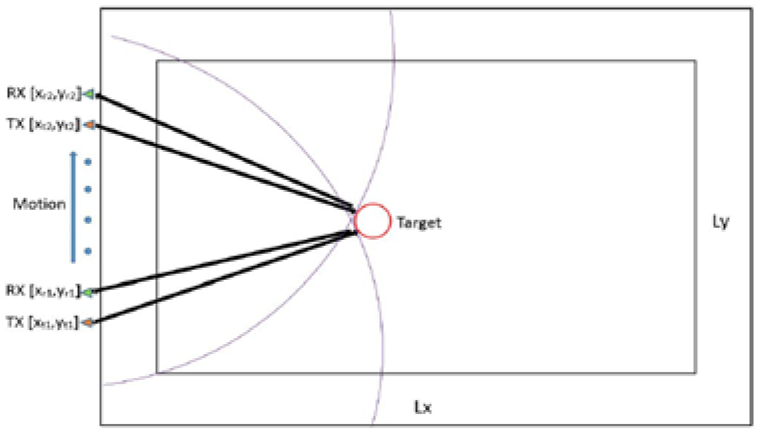


This novel approach to the detection of man-made objects offers important clutter suppression capabilities – a crucial element of false alarm rate mitigation.

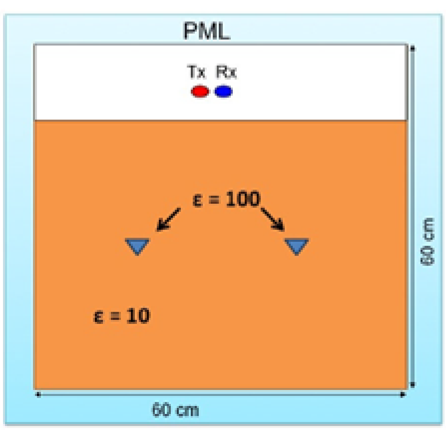
The PIRT team, working closely with ARL personnel, designed, built and tested (side by side with the Army) a novel UWB radar transceiver compatible with the ARL vision of a forward-looking radar. This hardware was modified to allow it to examine the utility of harmonic scattering from man-made targets. Because of positive results from extensive trials, the hardware designs and capabilities have been transitioned to ARL for further development.

Investigate the value of inverse scattering methods with complementary tasks to improve electromagnetic solvers. As we noted in the introduction, the PIRT team lost one of two primary investigators in this task area (the inverse scattering algorithm developer). Thus our progress was limited to the complementary effort to understand and evaluate the forward scattering problem. As an adjunct, we developed improved techniques for efficient and accurate electromagnetic solvers capable of predicting backscatter for missions of interest to the Army (i.e., predict IED signatures, penetration through walls and other obscuring materials, etc.).

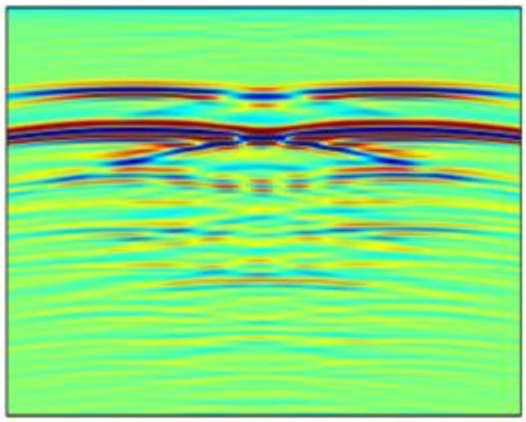
The finite-difference time-domain (FDTD) method is a widely used numerical technique for solving the time domain Maxwell's equations of electrodynamics. To accurately model small structures in relatively large computational domain, the sub-gridding technique is applied to save computational cost. We have developed a novel stable iteration based temporal sub-cycling FDTD algorithm for solving the Maxwell's equations in time domain. The stability of our method is analyzed using an eigenvalue test and verified by performing long time simulation of millions of steps. Through-the-wall radar imaging (TWRI) is emerging as a viable technology for providing high quality visual of enclosed structures. In our research, we apply the proposed temporal sub-cycling FDTD algorithm to simulate the through-the-wall radar (TWR) and employ a radar imaging method to reconstruct the object. First we show the target scenario. A circular object is located within a room with exterior walls shielding it from view. A wideband radar is moved along the exterior of one of the walls and the wideband data are collected and analyzed.



The similar problem of detecting an underground object immersed in a dielectric half-space (such as a landmine buried in the soil) has also been studied. We have implemented FDTD method to study this ground penetrating radar scenario. In order to suppress numerical errors, mesh refinement methods are applied such as the adaptive mesh refinement method and a newly developed Transformation Optics (TO) based local mesh refinement method. The following figures show the simulation setup and results for GPR simulations. Let us take the case of ground penetrating radar illuminating two dielectric targets within a dielectric half space:



The resulting false color encoded response from the modeled radar response is shown below:



By comparing modeled results with real world data measured by ARL engineers, we are able to verify the accuracy of our modeling approach.

We continue to refine the methodology behind the electromagnetic solvers to increase speed without sacrificing accuracy. This is a crucial factor which allows the computational space (hence, the target size) to become large enough to evaluate scenarios of interest to the Army. We have developed a novel stable local mesh refinement (LMR) algorithm based on the use of electric and magnetic anisotropic media and coordinate mapping. An important feature of this method is to use the invariance of the Maxwell equations after the coordinate transformation, while the materials become electrically and magnetically anisotropic. We magnify a small sub-region using coordinate stretching to create a virtual domain and then numerically solve the new full electrically and magnetically anisotropic Maxwell's equations in the logical Cartesian coordinates using a stable anisotropic Maxwell solver. The physical grid is a structured non-orthogonal mesh and the region being magnified has a finer gridwork than its nearby member, so this method is considered a local mesh refinement method. In comparison to the sub-gridding/AMR FDTD methods, one of the major advantages of our method is the proven stability property of the numerical methods applied to the anisotropic Maxwell equations. Our method differs from the traditional coordinate transformation approaches such as the curvilinear FDTD methods as our method changes both independent and dependent variables while other approaches only change the independent variables without corresponding field transformations and thus require temporal and/or spatial field interpolations that lead to late-time instabilities.

Other refinements include extending the sub-pixel smoothing Finite-Difference Time-Domain (FDTD) method to material interface between dielectric and dispersive media by local coordinate rotation. Our method is equivalent to the previously proposed sub-pixel smoothing method for dielectric interface, and the extension to dispersive/dielectric interface does not require split fields so our method has improved the efficiency in comparison to the previous proposed split field approach. A novel stable anisotropic FDTD algorithm based on the overlapping cells has been developed for solving Maxwell's equations of electrodynamics in anisotropic media with interface between anisotropic dielectrics and dispersive medium or Perfect Electric Conductor (PEC). The previous proposed conventional anisotropic FDTD methods suffer from the late-time instability due to the extrapolation of the field components near the material interface. Our anisotropic Overlapping Yee (OY) FDTD method is stable, as it relies on the overlapping cells to provide the collocated field values without any interpolation or extrapolation. Numerical results on eigenvalue analysis confirm that our method is stable. Finally, we have developed a moving window full Maxwell solver algorithm with perfectly matched absorbing layer (PML) boundary conditions in order to accurately simulate the propagation of localized waves over a very long distance (millions of wavelength) in complex media. An existing finite difference moving frame method developed more than a decade ago is inadequate due to low order transparent boundary conditions. Our method enables the realistic and predictive simulations of high intensity optical pulses in regime for which current direct Maxwell solvers are inapplicable due to memory and CPU requirements.

The PIRT team has developed new approaches to computational electromagnetic that offer faster execution without compromising accuracy. We have applied these novel codes to predict performance of wideband radar in the concealed target scenarios of most interest to our Army colleagues.

IED detection from an improved multi-sensor fusion paradigm. IED defeat through reliable detection and location of often hidden explosives along (and under) roadways remains an incredibly difficult technical challenge. We have already discussed our contributions to (non-linear) imaging algorithms to minimize clutter competition for forward-looking radar. We have also reviewed the important radar transceiver development we undertook in partnership with ARL. This offers the capability to avoid the more serious radio frequency interference found within the preferred operating spectrum of a wideband ground penetrating radar. An adjunct to that development was a parallel receiver channel capable of detecting second harmonic scattering – a phenomenology strictly associated with man-made targets (thus aiding in the separation of targets from naturally occurring clutter). Finally, we discussed our advances in computational electromagnetics which promote accurate predictions of target backscatter for targets of interest. However, even with the scope of these advances, reliable detection of IEDs at a tolerable false alarm rate remains elusive.

Army researchers have long recognized the challenge of IED detection using only a single sensor technology. Despite the high potential of UWB forward-looking radar, near perfect decision making is a stretch goal. Thus finding constructive techniques to combine many sensor modalities is an important objective for ARL engineers. Of particular interest, in the forward-looking geometry, is the combination of radar, optical cameras and infrared cameras. The forward-looking radar geometry inherently provides at least crude three dimensional imaging. By use of stereo vision (i.e., two or more cameras separated by a baseline), both optical and thermal 3D image reconstruction is possible. We postulate that by organizing disparate sensor imagery in an aligned and geo-referenced gridwork, superior detection performance might be achieved. Further, the co-aligned gridwork supports a variety of image visualizations for the crew-served sensor platform. These enhanced visuals are sometimes referred to as “augmented reality” by Army researchers.

The PIRT team, working closely with ARL personnel, has taken a number of positive steps towards realizing a much improved multi-sensor paradigm. Tasks such as single sensor calibration, invoking stereo vision from paired optical sensors (separated by a baseline), aligning multiple sensor modes with differing frames of reference, geo-referencing each sensor data stream, visualizing multi-sensor data and, ultimately, combining individual data sets in a coherent approach to sensor fusion all required maturation. As a reminder, the Army operates a forward looking sensor testbed where both radar and optical data are collected from the rooftop mounting platform (as seen below):

The PIRT team assisted the Army in augmenting the original SAFIRE (i.e., radar) platform with both optical and thermal stereo vision. Inside the vehicle, the discrete data streams were tagged with positional data to allow geo-referencing as well as near realtime visualization. The archived data would then be returned to the lab for further processing and assessment.

To realize this capability the following tasks were completed:

1. Designing and constructing a multimodal stereo system including two thermal and two color cameras working in conjunction with the SAFIRE radar system;
2. Development of Color-Thermal calibration techniques;
3. Development of Camera-Radar alignment techniques;
4. Release of a multimodal graphical user interface to display aligned 2D color, thermal, and/or radar imagery with slider bars for the user to control how to mix the modalities and threshold the radar;
5. Development of code to perform 3D stereo reconstruction;
6. Construction of a multimodal stereo dataset for testing 3D algorithms;
7. Alignment of color, thermal, and radar imagery in 3D space with the capability to view reconstructions from a single frame;
8. Successful testing of the system at the Yuma Proving Grounds;

9. Development of code to use color and thermal imagery to automatically detect anomalous objects in a scene with Gaussian Mixture Models; and

10. Starting work towards multimodal fusion of all sensors for automatic target detection and classification using deep Convolutional Neural Networks.

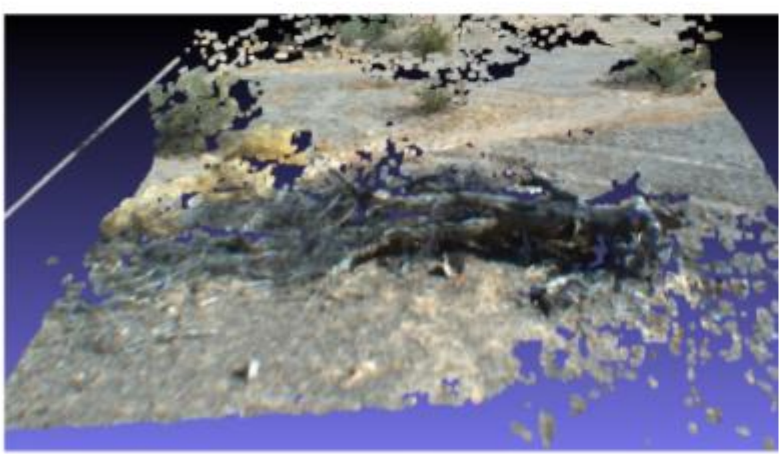
Initially, the multimodal system was designed to obtain color, thermal, and depth information from the camera, which can be used to augment the radar for detection and classification of hidden targets. The camera system and radar were first constructed and tested at the Army Research Lab in an indoor location with synthetic scenes in a sand pit. Here, the cameras and radar were all aligned manually.

To facilitate automatic alignment between the sensors, a color-thermal calibration technique was developed. By using a ceramic calibration board with a printed checkerboard, the pattern would be visible in both modalities and would be suitable for camera calibration. Using the sun as a heat source was more effective due to the uniform heating; this is especially applicable for use real desert conditions. The procedure was automated to a point where a non specialist was able to calibrate the camera without assistance in 2017 during testing at the Army's Yuma facility.

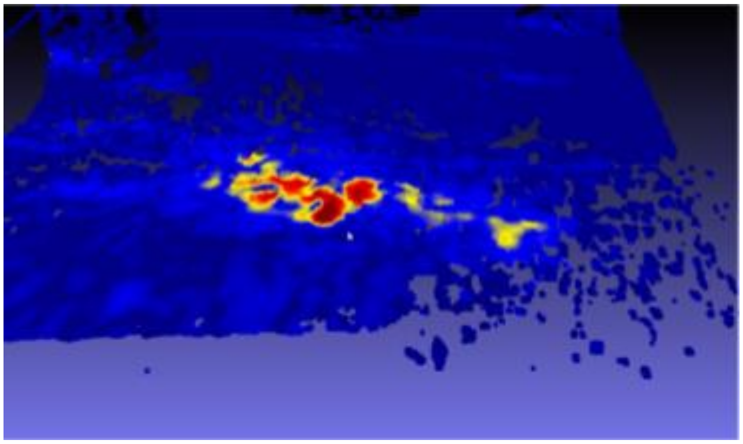
Next, we needed to align the camera system to the radar. The problem is posed as a 3D-2D projection from the 3D world coordinates of the radar to discrete camera pixel locations. By using the GPS/IMU on the truck, on top of the calibration procedure already discussed, multiple transformation matrices are calculated automatically. To display the results, a graphical interface was developed to show the overlay between color, thermal, and radar. Slider bars allow the user to choose how much of each sensor to use, and allow the user to threshold the radar imagery to show only the strongest responses:

In 2016 and 2017, the system was deployed to the Army's Yuma Proving Grounds for testing. Scenes including realistic targets hidden in various locations were imaged with the composite system. The stereo cameras were used to create 3D reconstructions of the desert scenes. Stereo matching algorithms from Computer Vision were implemented to give dense point clouds and 2.5D imagery that give shape and depth information of objects within the scene. The 3D reconstructions were created for every frame in a video sequence. All three sensor types can be viewed in 3D for a single frame at a time. First, we show a conventional 2D picture of the area under test. Notice the large surface clutter items scattered around the arid terrain that is typical of Yuma:

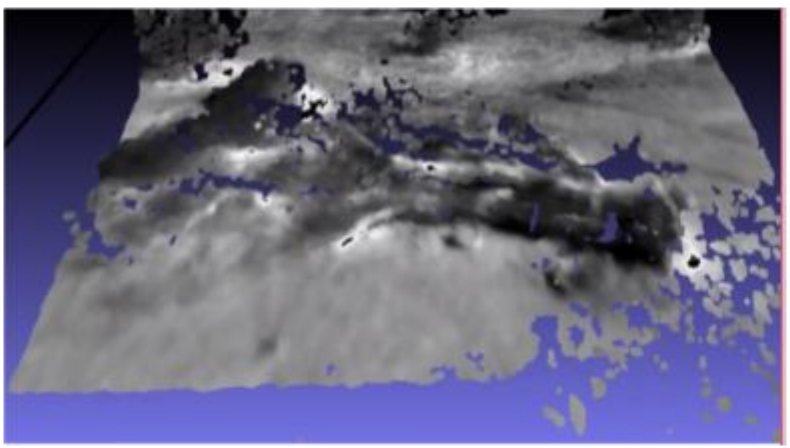
Next we show an optical 3D reconstruction of the same area concentrating on the large clutter object in the foreground. An operator needs to assess whether an IED may be hidden within or underneath the various branches. The 3D visual allows us to “peer” into the clutter object and investigate if a man-made object may be hidden within.



Then we assess the radar backscatter from the same scene. A larger, man-made object with metal content or smooth shape may generate significant radar return. The false color encoded image is shown below:



Finally, we look at a 3D reconstruction of a thermal image pair interrogating the same scene. A metal object may heat and cool at a different rate than the natural background leading to “hot spots” within the scene. The reconstruction follows:



Note the effort described above results in an aligned and geo-referenced data set which facilitates comparing and contrasting the results from each of the individual sensors. By exploiting unique phenomenology in an optimized fashion, superior detection performance may obtain.

To train and test stereo matching algorithms, the Color and Thermal Stereo dataset (CATS) was developed. The dataset included thousands of multi-modal imagery with corresponding 3D ground truth locations generated from a LIDAR.

To move toward automatic detection and classification of targets using the system, several methods have been proposed and evaluated. We use color and thermal information to identify suspicious targets and then fuse color, thermal, and radar information for detection. Initial test results have been shared with ARL researchers for assessment of potential. With future interest from ARL, we intend to collect enough data to train a Deep Convolutional Neural Network for automatic recognition of known targets.

The PIRT team served as co-investigators with ARL personnel in the pursuit of mechanizing and testing a multi-sensor testbed for IED defeat. Working side by side with Army engineers, we helped define and architect a sensor fusion approach that will permit ARL to determine the degree of improvement available with a combined sensor platform.

Summary

The PIRT members (from DSU, Penn State and University of Delaware) are quite proud of the many accomplishments we have achieved during the conduct of the Army's PIRT project. From inception, the Army emphasized an innovative approach to procuring technology that would result in tangible transitions during the duration of the program. We believe we have lived up to that demanding goal and have delivered:

- Novel image formation approaches that are now routinely used by the Army
- A completely new transceiver architecture and hardware that has supplanted the impulse radar approach formerly used by ARL
- An initial cut at using the new transceiver architecture to support harmonic radar for man-made object detection
- Software to enable alignment and geo-referencing of sensors of interest to ARL in the IED defeat mission
- Novel image visualizations for forward-looking sensors to realize the ARL vision of "augmented reality"
- Advice on optical sensor selection and software to enable 3D reconstructions from stereo optical sensors – both conventional day TV as well as thermal
- Development of a framework for multi-sensor fusion that will ultimately improve IED detection and location
- Finally and, perhaps most importantly, we have transitioned our most important assets – our students who have joined the Army team after completing their studies at our respective institutions.

We like to believe our PIRT project is a benchmark of how university's can successfully interact with Army colleagues to realize important advances in R&D with tangible transition products to satisfy a national priority – in this case the defeat of IEDs.